Accelerator Driven High Energy Density Physics Requirements

John Barnard

High Energy Density Physics Workshop

May 24-26, 2004

Gaithersburg, Maryland

(with many thanks for contributions from Debbie Callahan, Max Tabak, Richard Lee, Dale Welch, Richard Briggs, Alex Friedman, Ed Lee, Grant Logan, Jay Marx, Andy Sessler, Jonathan Wurtele, Simon Yu,)

Outline

Requirements of accelerator driven WDM physics

Need for neutralized drift compression and focus

Target temperature uniformity and velocity spread

Physics of neutralized drift compression

- Shorter pulses obtainable
- Focus must be tolerant of large velocity spread
- Filamentation, two-stream instability, transitions

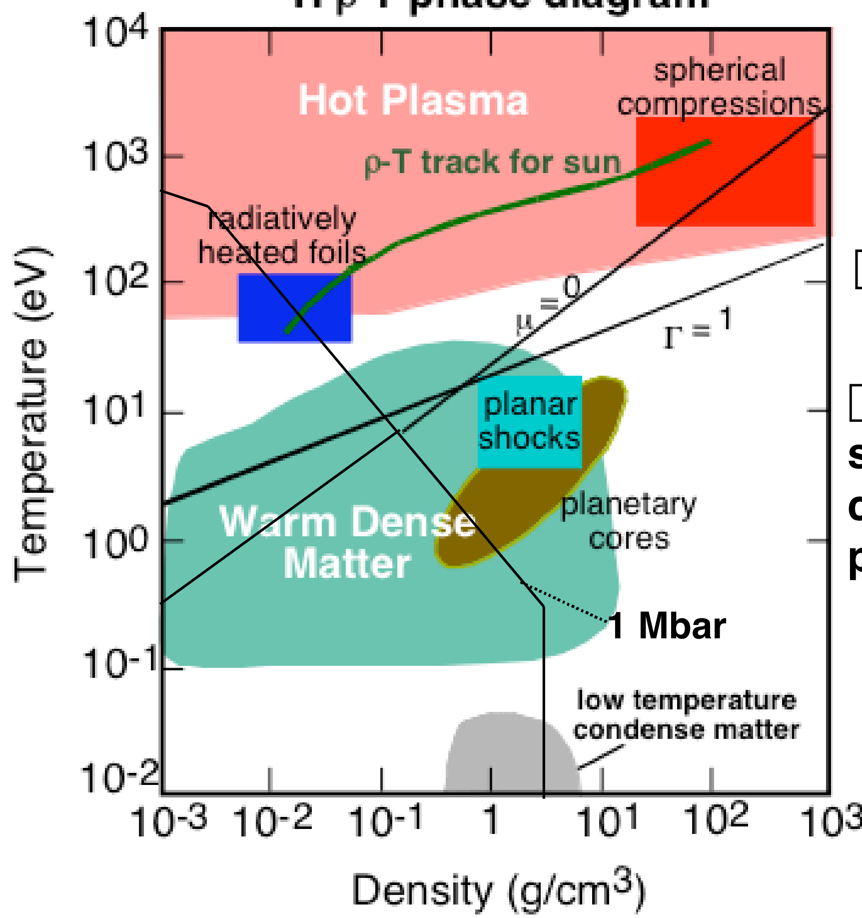
Simulation example of near term experiment

From R. Lee's HEDP talk at LBNL, 9/22/2003:

High Energy Density matter is interesting because it occurs widely

- **Hot Dense Matter (HDM) occurs in:**
  - Supernova, stellar interiors, accretion disks
  - Plasma devices: laser produced plasmas, Z-pinches
  - Directly driven inertial fusion plasma
- **Warm Dense Matter (WDM) occurs in:**
  - Cores of large planets
  - Systems that start solid and end as a plasma
  - X-ray driven inertial fusion implosion

H ρ-T phase diagram



$$\Gamma = \frac{q^2 n^{1/3}}{kT}$$

Γ > 1 => strongly coupled plasmas

HEDP definition: U> 10^{11} J/m^3; P> 1 Mbar; kT > 1eV at Γ=1

Basic Requirements

Temperature T > ~ 1 eV to study WDM
Energy Density U ~ 10^{11} - 10^{12} J/m^3
Pressure P ~ 1 - 10 MBar
Strong Coupling Constant □ > ~ 1

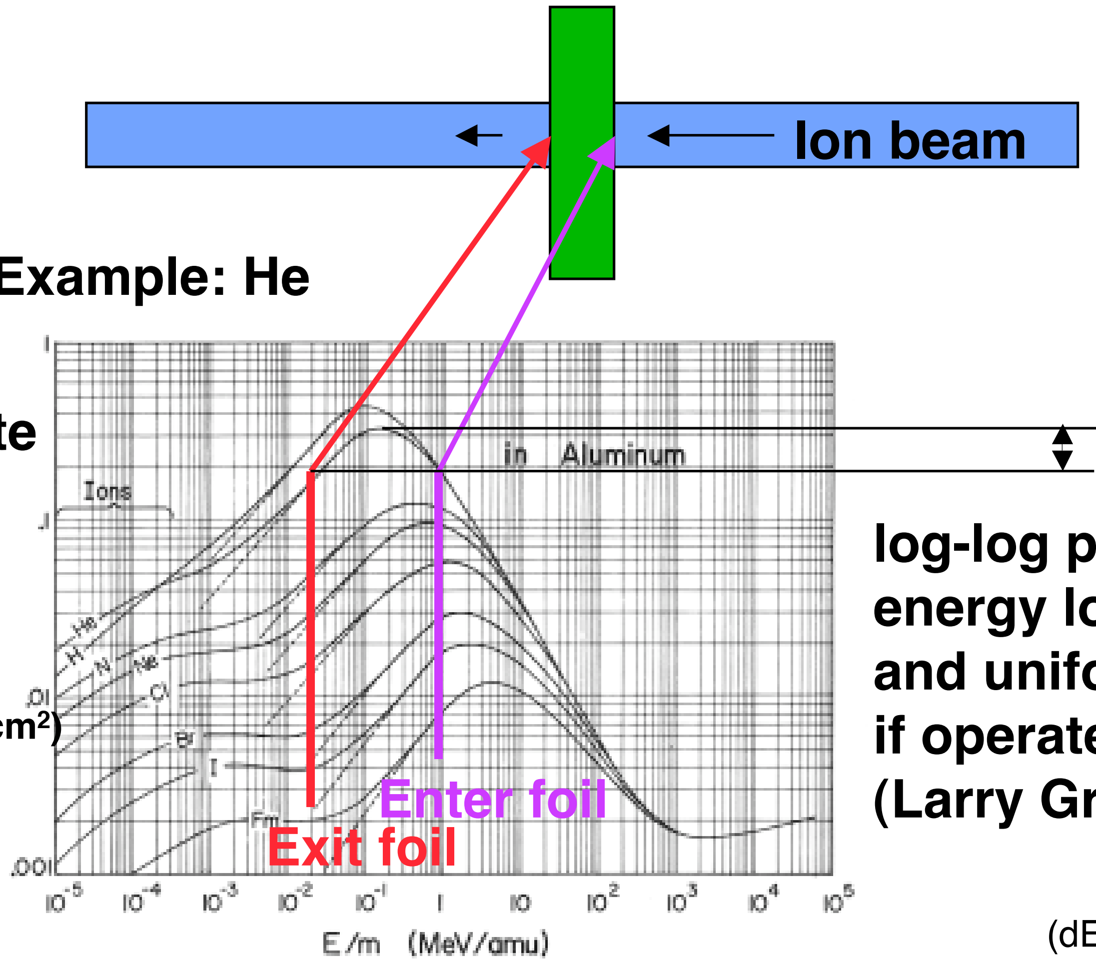
For isochoric heating: □t must be short enough to avoid cooling from hydrodynamic expansion (to be explained)

Uniformity: □T/T < ~5% (to distinguish various equations of state)

Timescale for building accelerator: ~ 10 years

Strategy: maximize uniformity and the efficient use of beam energy by placing center of foil at Bragg peak

In simplest example, target is a foil of solid or "foam" metal



Energy loss rate

$\square\frac{1}{Z^2}\frac{dE}{dX}$

(MeV/mg cm^2)

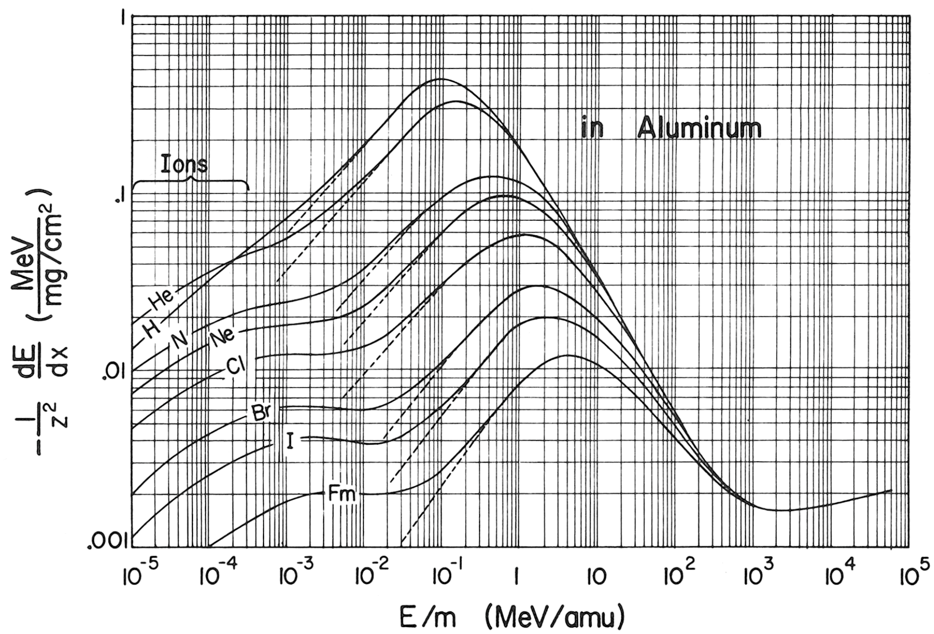
Energy/Ion mass **(MeV/amu)**

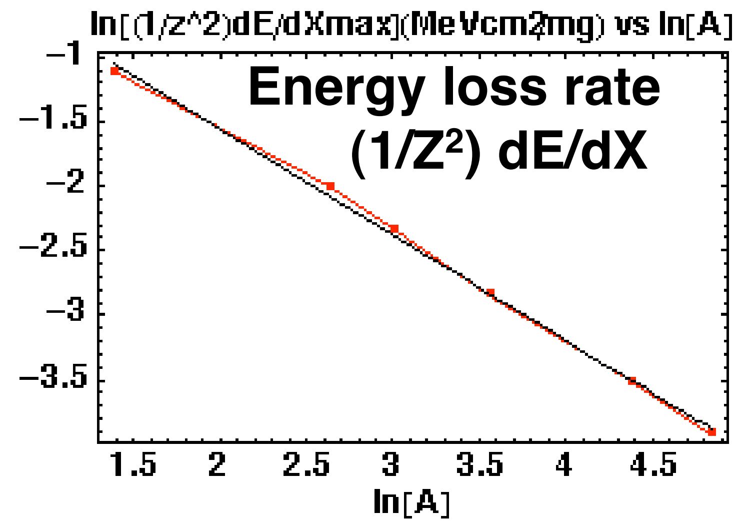
□dE/dX µ □T

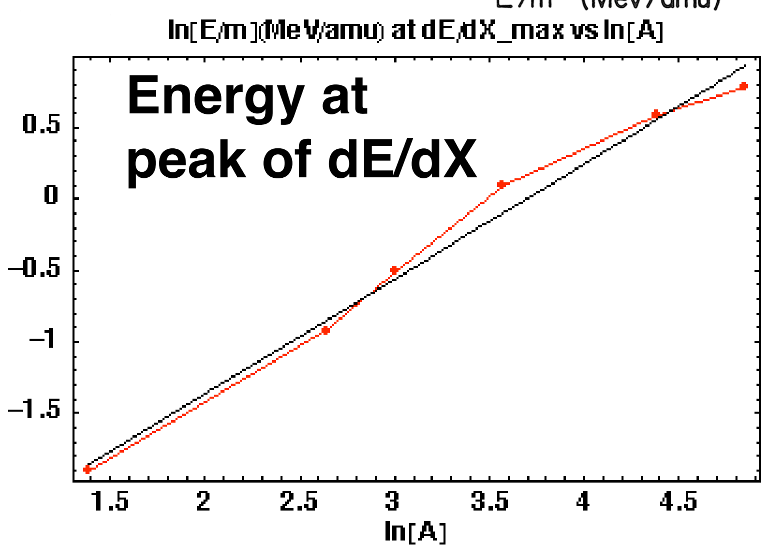
log-log plot => fractional energy loss can be high and uniformity also high if operate at Bragg peak (Larry Grisham, PPPL)

(dEdX figure from L.C Northcliffe and R.F.Schilling, Nuclear Data Tables, **A7**, 233 (1970))

Increasing ion mass, increases energy of Bragg peak, and energy loss rate at Bragg peak







For 4 < A < 126 (He -> I):

Energy at maximum dE/dX:

$E_{dE/dXmax} \sim 0.052$ MeV $A^{1.803}$

Energy loss rate at maximum dE/dX:

$(1/Z^2)dE/dX_{max} \sim 1.09$ (MeVcm^2/mg) $A^{-0.82}$

$dE/dX_{max} \sim 0.35$ (MeVcm^2/mg) $A^{1.07}$

Some scalings

E (at dE/dX_{max}) =~ 0.052 MeV $A^{1.803}$

$\Delta E/E = \sim < 0.62$ **(for a 5% change in dE/dX)**

$Z = 2\Delta E/(\rho\, dE/dX) = \sim 0.77\mu \quad A^{0.733}(\rho_{al}/\rho)$

Energy density increases with higher ρ, larger A:

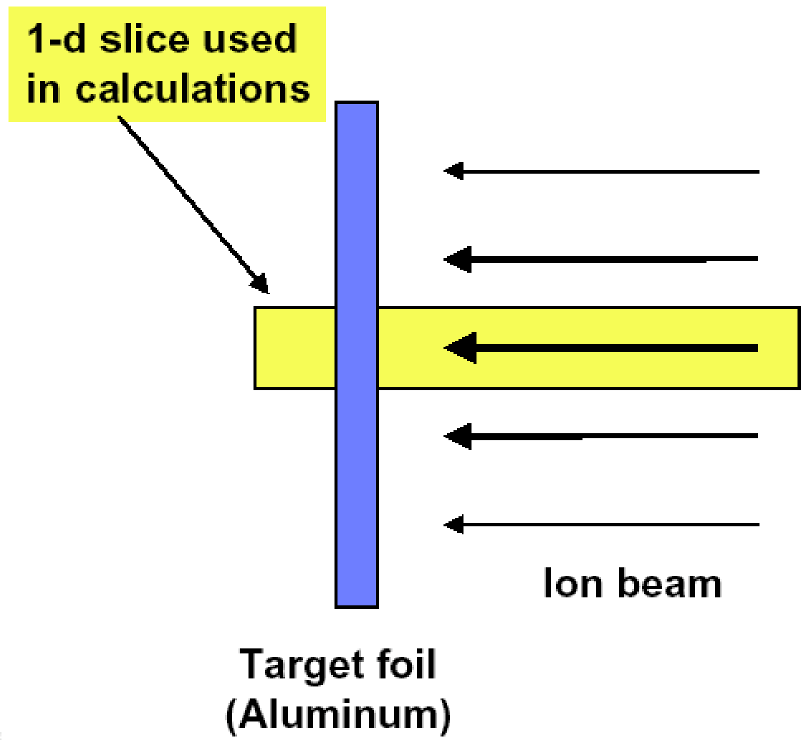
$$U = \frac{N_{ions}E}{\pi r^2 Z} = 3.7 \times 10^9 \frac{\mathrm{J}}{\mathrm{m}^3}\left(\frac{N_{ions}}{10^{12}}\right)\left(\frac{1\ \mathrm{mm}}{r}\right)^2\left(\frac{\rho}{\rho_{al}}\right)A^{1.07}$$

Hydro time increases with lower ρ, and weakly on larger A:

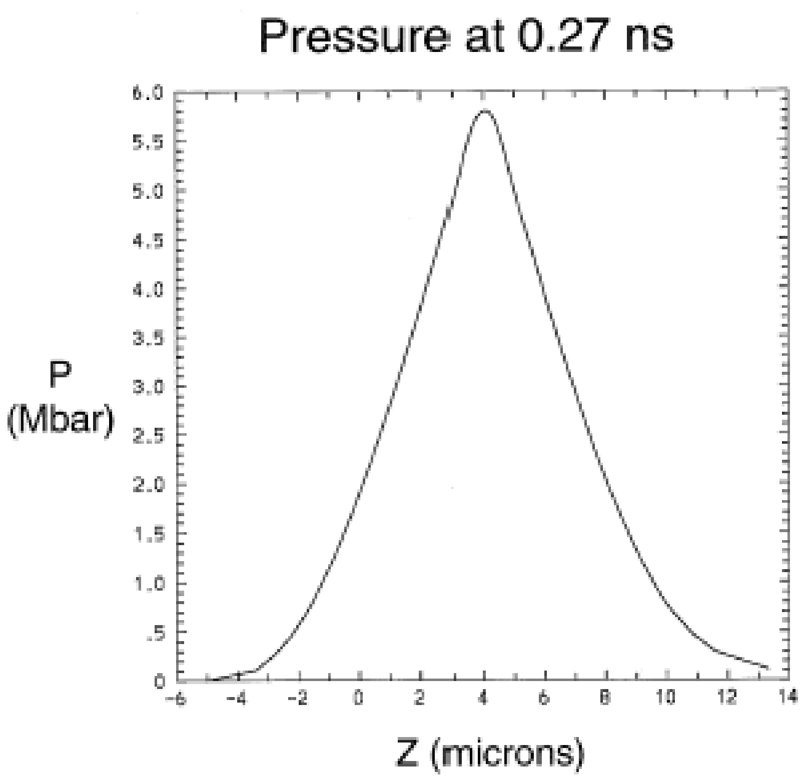
$$t_{hydro} = Z/c_s = \frac{Z}{\sqrt{\gamma(\gamma - 1)U/\rho}} = 0.6 \times 10^{-9}\mathrm{s}\left(\frac{10^{12}}{N_{ions}}\right)^{1/2}\left(\frac{r}{1\ \mathrm{mm}}\right)\left(\frac{\rho_{al}}{\rho}\right)A^{0.198}$$

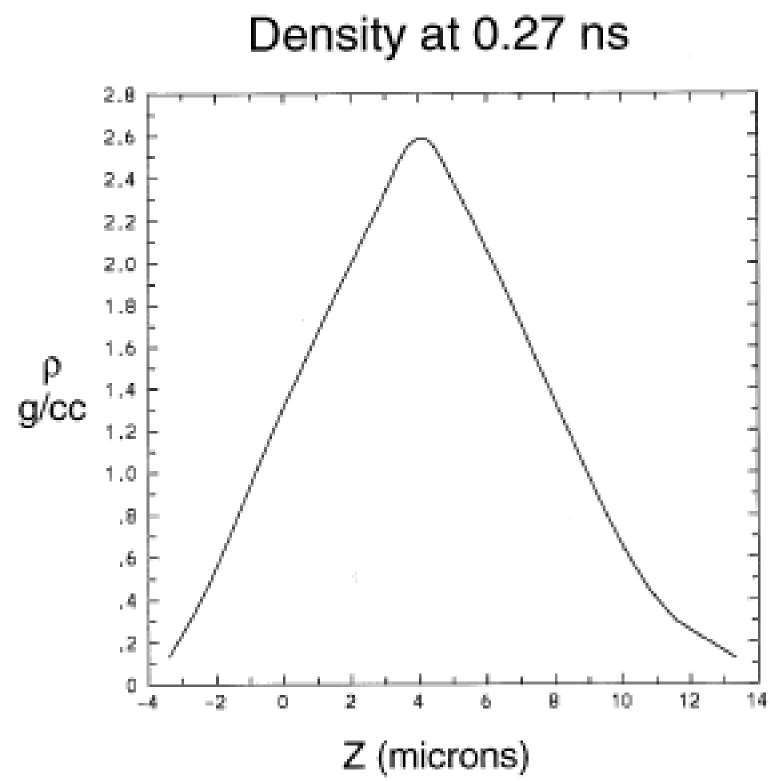
Simulations were carried out by D. Callahan, to explore hydrodynamic effects

- 1-d calculations for the center of the beam
  - Assuming a 1 mm radius Gaussian beam, used 2% of the energy in a 100 micron radius spot
  - 2-d and 3-d effects will make the target expand faster
- "2015" machine
  - Ne^{+1} ion
  - 30 MeV kinetic energy
  - 1 mm radius at best focus
  - 0.5 ns pulse duration
  - 30 J total beam energy
  - 20 - 40 MeV energy spread
  - 60 GW power
  - 3.8 TW/cm^2 center of beam



Because the pulse duration is still long, the target has expanded and is non-uniform

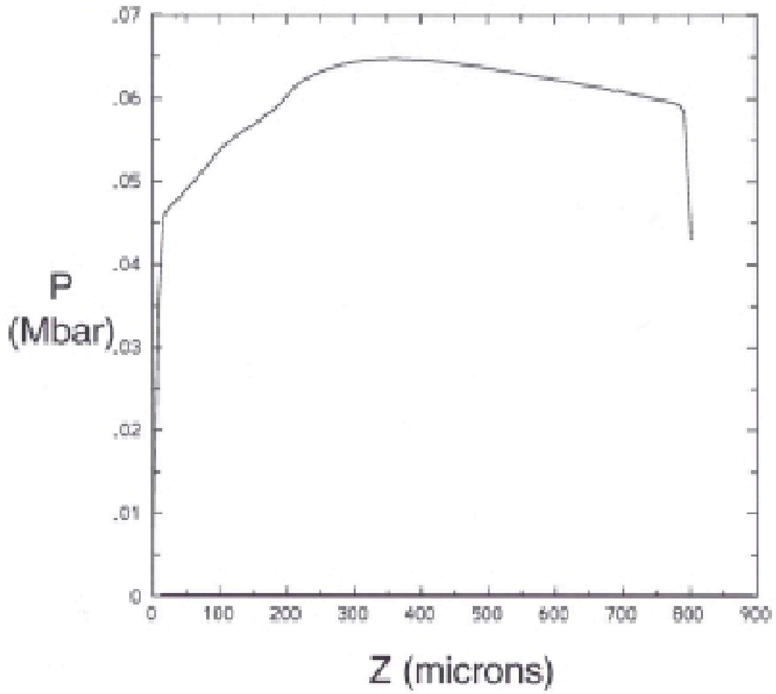


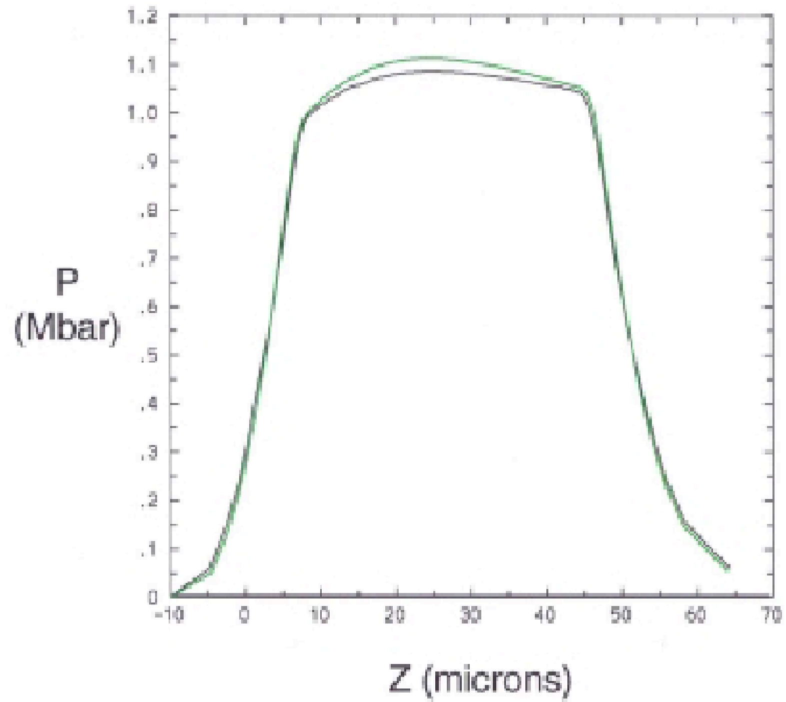


Target was initially 8 microns thick at 2.7 g/cc

(slide courtesy D. Callahan, LLNL)

Using a low density target with the "2015" machine results in more uniformity, but less energy density





1% solid density
800 microns thick

15% solid density
53 microns thick

(slide courtesy D. Callahan and M. Tabak, LLNL)

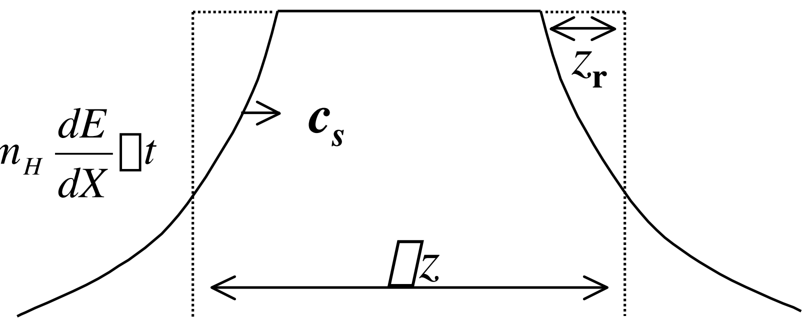
For larger targets ($\Delta z > \Delta z_{min} \sim 40\ \mu$), pulse duration can be significantly longer

$$\frac{dkT}{dt} = \frac{2}{3}\frac{J}{e}\square m_H \frac{dE}{dX}$$

If $\square$, J, and $\frac{dE}{dX}$ constant, then $\frac{T}{T_*} = \frac{t}{\Delta t}$ where $kT_* = \frac{2}{3}\frac{J}{e}\square m_H \frac{dE}{dX}\Delta t$

$$c_s = \sqrt{\frac{\gamma P}{\rho}} \propto T^{1/2} \propto t^{1/2}$$

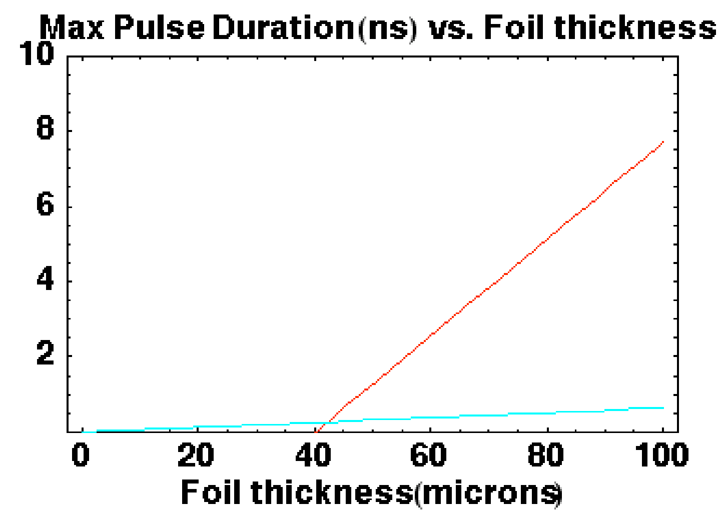
$$z_r = \int_0^t c_s\,dt = \frac{2}{3}c_{s*}\Delta t\left(\frac{t}{\Delta t}\right)^{3/2} \quad \text{where } c_{s*} = c_s(T_*)$$



Rarefaction wave propagates inward at c_s (increasing with time)

Δz_{min} is the minimum length in z for which diagnostics may interrogate the region of interest. We assume $\Delta z_{min} = 40\ \mu$ in this example.

$$\Delta t \approx \begin{cases} \dfrac{(\Delta z - \Delta z_{min})}{2(2c_{s*}/3)} & \text{for } \Delta z > \Delta z_{min} \\[2ex] \dfrac{\Delta z}{2(20)(2c_{s*}/3)} & \text{for } \Delta z < \Delta z_{min} \end{cases}$$



Example parameters: Ne^{+1} beam

Ne: Z=10, A=20.17, E_{min}=4.4 MeV, E_{center}=11.7 MeV, E_{max}=19 MeV
□z_{min} = 40 □

□(g/cm^3)(%solid)	0.027 (1%)			0.27 (10%)			2.7 (100%)		
Foil length (□)	700			70			7		
kT (eV)	3.5	7.9	15.	4.5	15	20	7.1	31	38
□□	1.2	2.6	3.1	0.95	2.7	3.0	0.69	2.8	3.1
$□_{ii}=Z^{*2}e^2n_i^{1/3}/kT$	0.51	1.0	0.92	0.53	1.3	1.2	0.38	1.5	1.4
$N_{ions}/(r_{spot}/1mm)^2/10^{12}$	2.24	7.96	22.4	2.24	14	22.4	2.24	22.4	30
□t (ns)	56	30	18	2.5	1.0	0.8	0.03	0.01	.008
U $(J/m^3)/10^{11}$	.021	.073	0.21	0.21	1.27	2.1	2.1	21	28

(Eq. of state, Z*: Zeldovich and Raizer model from R.J. Harrach and F. J. Rogers, J. Appl. Phys. **52**, 5592, (1981).)

Example parameters: Cl^{+1} beam

Cl: Z=17, A=35.453, E_{min}=12.3 MeV, E_{center}=32.4 MeV, E_{max}=52.4 MeV
□z_{min} = 40 □

□(g/cm^3)(%solid)	0.027 (1%)			0.27 (10%)			2.7 (100%)		
Foil length (□)	1050			105			10.5		
kT (eV)	3.5	7.9	15.	4.6	15	20	7.1	31	38
□$^□$	1.2	2.6	3.1	0.96	2.7	3.0	0.69	2.8	3.1
□$_{ii}$=$Z^{*2}e^2n_i^{1/3}/kT$	0.51	1.0	0.76	0.53	1.3	1.1	0.38	1.5	1.4
$N_{ions}/(r_{spot}/1mm)^2$ $/10^{12}$	1.24	4.3	12.4	1.24	8.0	12.4	1.24	12.4	16
□t (ns)	87	46	27	5.6	2.2	1.8	0.045	0.014	.012
U (J/m^3)/10^{11}	.021	.073	0.21	0.21	1.35	2.1	2.1	21	28

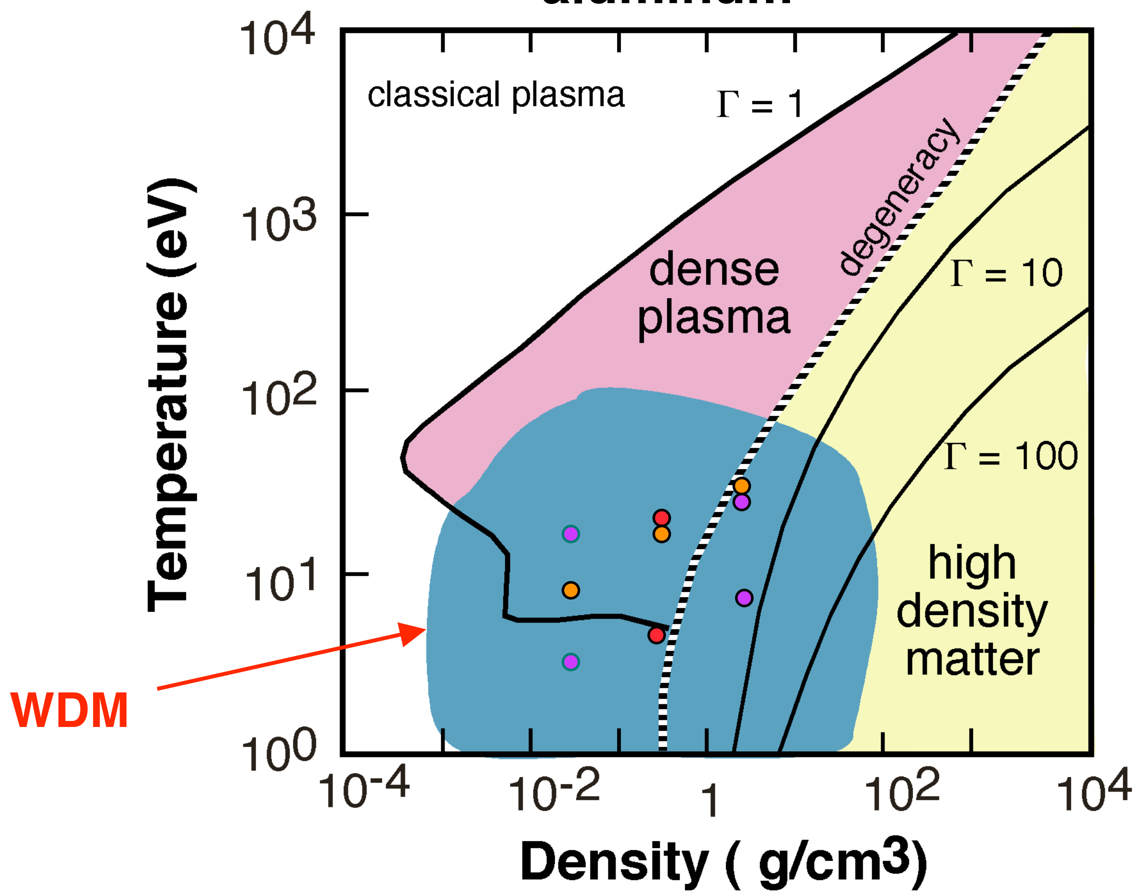
(Eq. of state, Z*: Zeldovich and Raizer model from R.J. Harrach and F. J. Rogers, J. Appl. Phys. **52**, 5592, (1981).)

Defining the Warm Dense Matter regime

WDM is that region in temperature (T) - density (ρ) space:

1) **Not described as normal condensed matter, i.e., T ~ 0**
2) **Not described by weakly coupled plasma theory**

aluminum



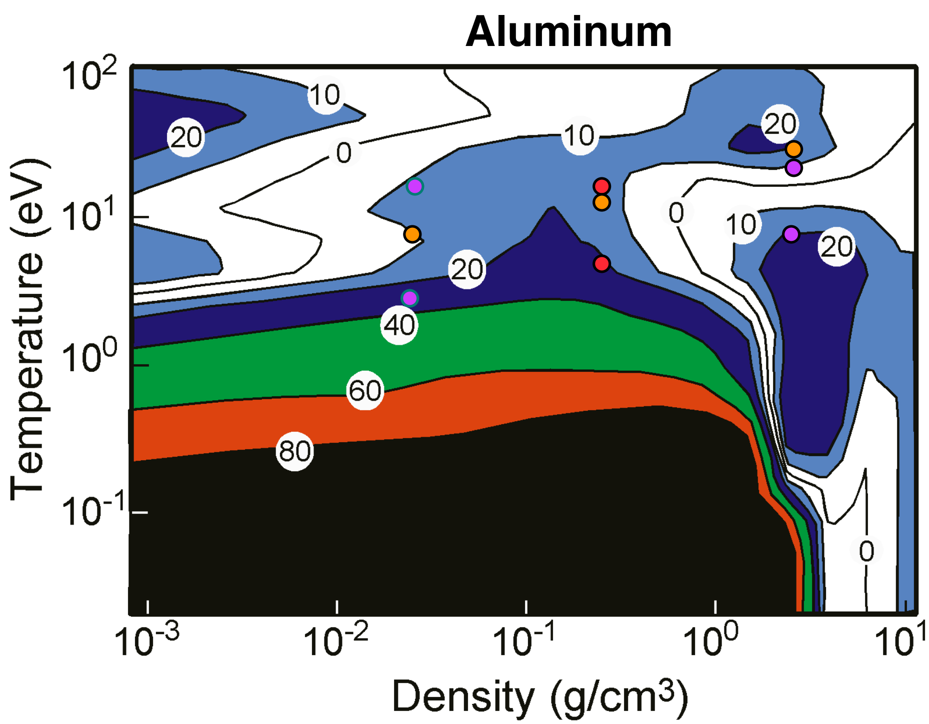
- Γ is the strong coupling parameter, the ratio of the interaction energy between the particles, V_{ii}, to the kinetic energy, T
- $$\Gamma = \frac{V_{ii}}{T} = \frac{Z^2 e^2}{r_o T}$$

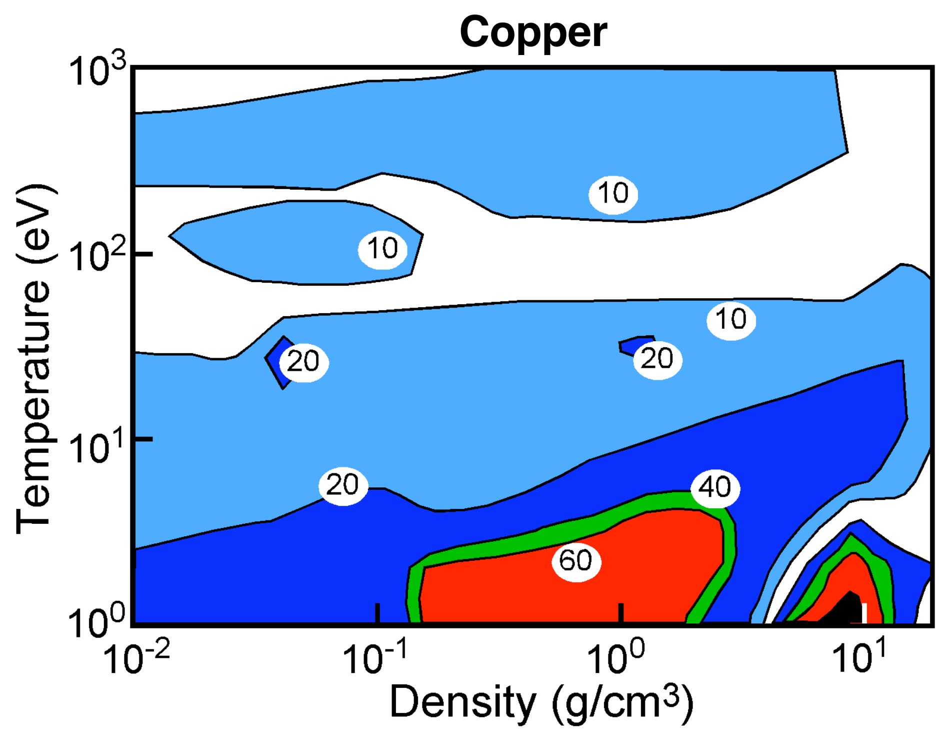
where $r_o \quad \frac{1}{\rho^{1/3}}$

(slide courtesy R. Lee, LLNL)

In Warm Dense Matter regime large errors exist even for most studied materials (slide courtesy R. Lee, LLNL)

Contours of % differences in pressure





- EOS Differences > 80% are common
- Measurements are *essential* for guidance
- Where there is data the models agree!!
  - Data is along the Hugoniot - single shock ρ-T-P response curve

Accelerator to achieve WDM is challenging -- explores new beam physics regimes

Consider:

19 MeV Ne^+ beam, Δt = 1 ns, N_{ions}=1.4 x 10^{13} particles

Then:

β ~ 0.045;

Bunch length $l_b = \beta c\ \Delta t$ = 1.4 cm

Line charge = $eN_{ions}/\ l_b$=160 μC/m

$E_z \sim eN_{ions}/4\pi\varepsilon_0\ l_b^2$ ~ 100 MV/m

So just to keep beam together requires substantial electric field. (1-2 MV/m typical “limit” in induction linac). So instead: use plasma to neutralize beam

Neutralized drift compression allows possibility of very short pulses

For a parabolic pulse the longitudinal envelope equation (including longitudinal thermal spread) for bunch length l is:

$$\frac{d^2 l}{dt^2} = \frac{16\varepsilon_z^2}{l^3} + \frac{4v_0^2 g Q_a l_a}{l^2} \qquad | \; | \qquad \left(\frac{\Delta v}{v}\right)_{tilt}^2 = 20\left(\frac{\Delta v}{v}\right)_a^2 \left[C^2 - 1\right] + 8gQ_a\left[C - 1\right]$$

Thermal Spread + Space Charge

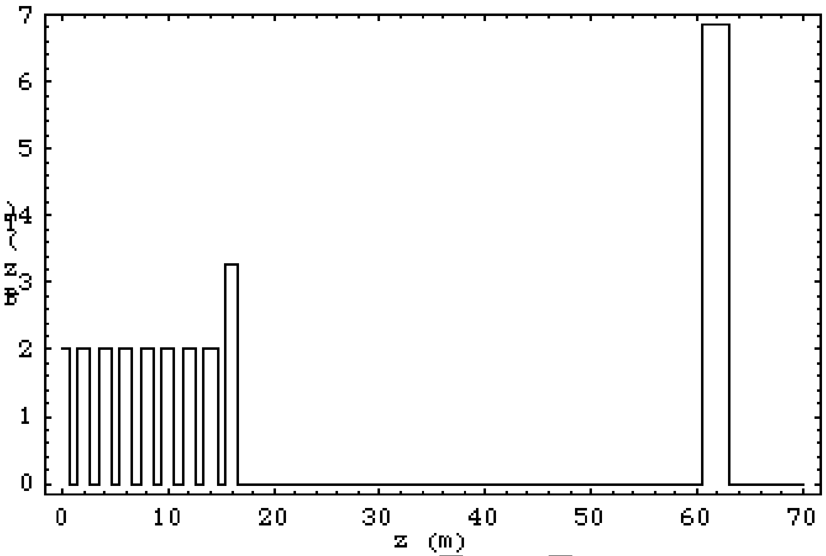
where $\varepsilon_z^2 \equiv 25\left(\langle \delta v_z^2\rangle\langle \delta z^2\rangle - \langle \delta v_z \delta z\rangle^2\right)$

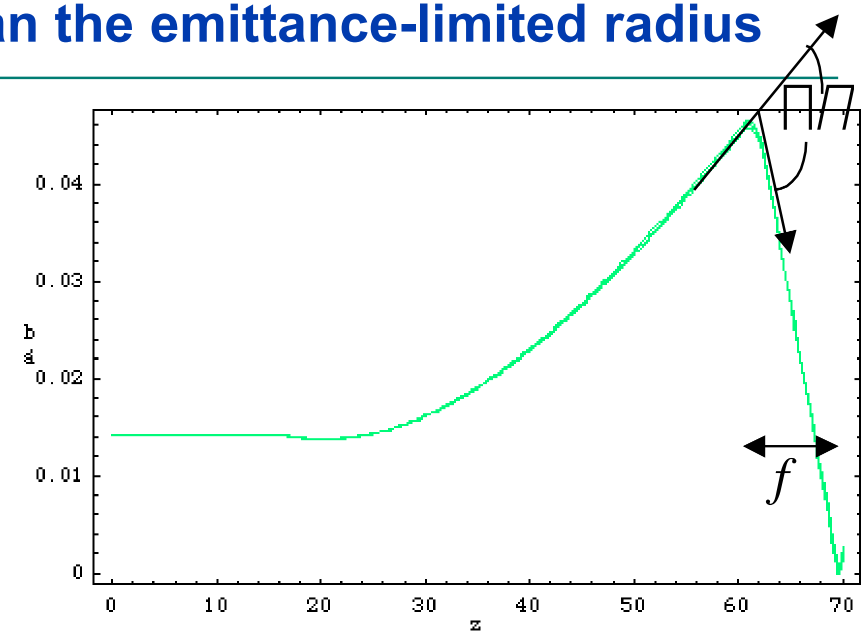
So if velocity spread at end of accelerator $\Delta v/v_a \sim 5 \times 10^{-4}$, initial tilt $\Delta v/v$ <~ 1, and perveance in drift section Q_a = ~0:

$$C_{max} = \left(\frac{[\Delta v/v]_{tilt}^2}{20[\Delta v/v]_a^2} + 1\right)^{1/2} \approx \frac{\Delta v/v_{tilt}}{4.5\,\Delta v/v_a}$$

(example: $\Delta v/v_{tilt} = 1$, $\Delta v/v_a = 5 \times 10^{-4}$,
==> $C_{max} = 450$)

A range in ion velocities, implies a range in focal lengths, and a focal spot radius which is larger than the emittance-limited radius

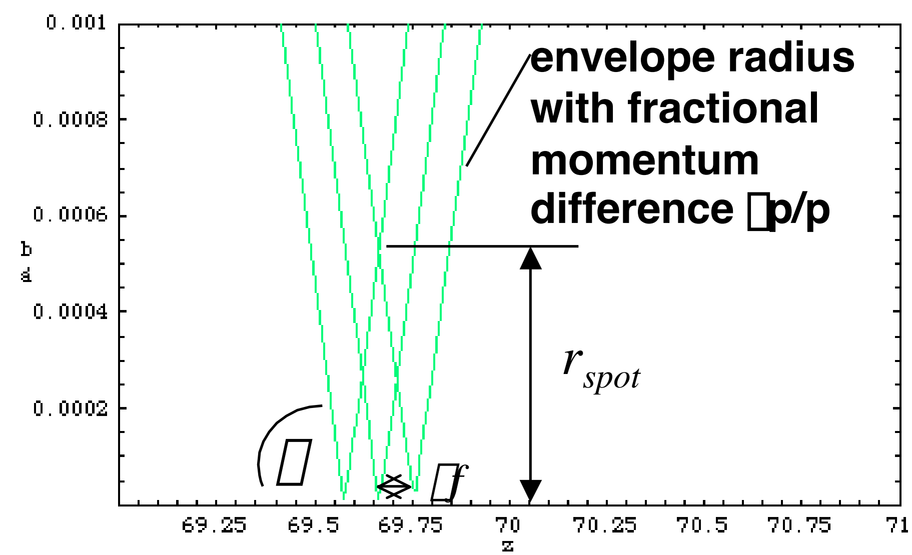




$$r_{spot} = \theta\Delta f = \theta\left(\frac{df}{d\kappa}\frac{d\kappa}{dp}\right)\Delta p$$

$$= \theta\left(\frac{f}{\kappa}\frac{2\kappa}{p}\right)\Delta p$$

$$r_{spot} \approx 2f\theta(\Delta p/p)$$



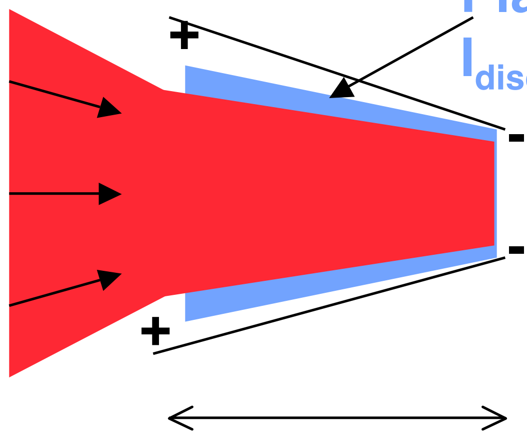
For "point-to-point" focus $\theta' = 2\theta$

$$r_{spot} \approx 4f\theta(\Delta p/p)$$

"Adiabatic plasma lens" can be used as a final focusing optic with large velocity acceptance

Plasma discharge:
$I_{discharge}$ ~ 100 kA

Beam coming from final solenoid

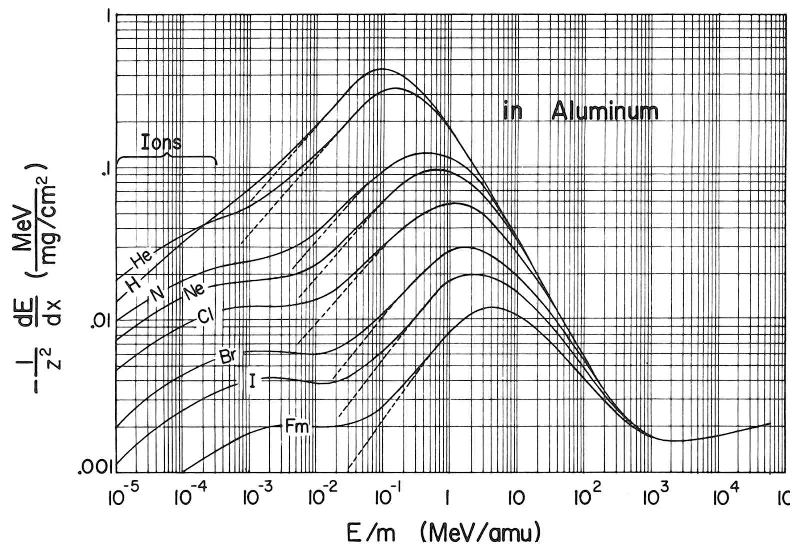


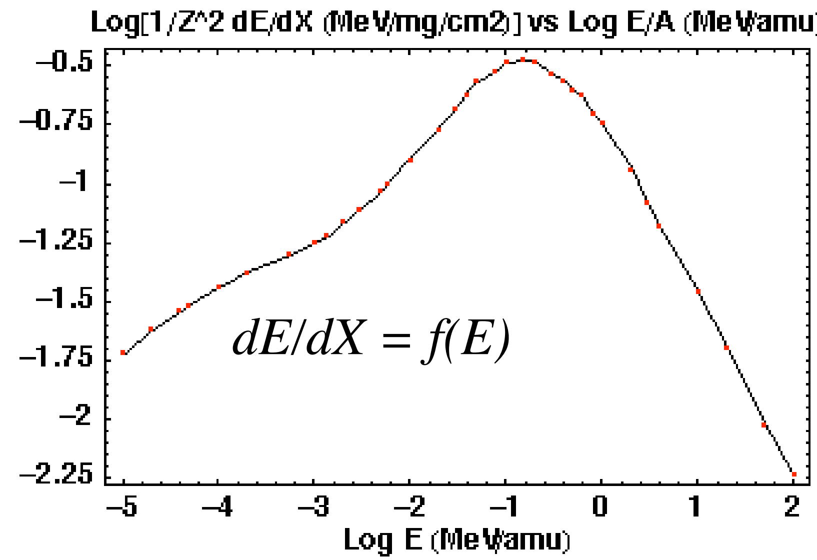
B_θ from discharge current x v_z from beam provides focusing force

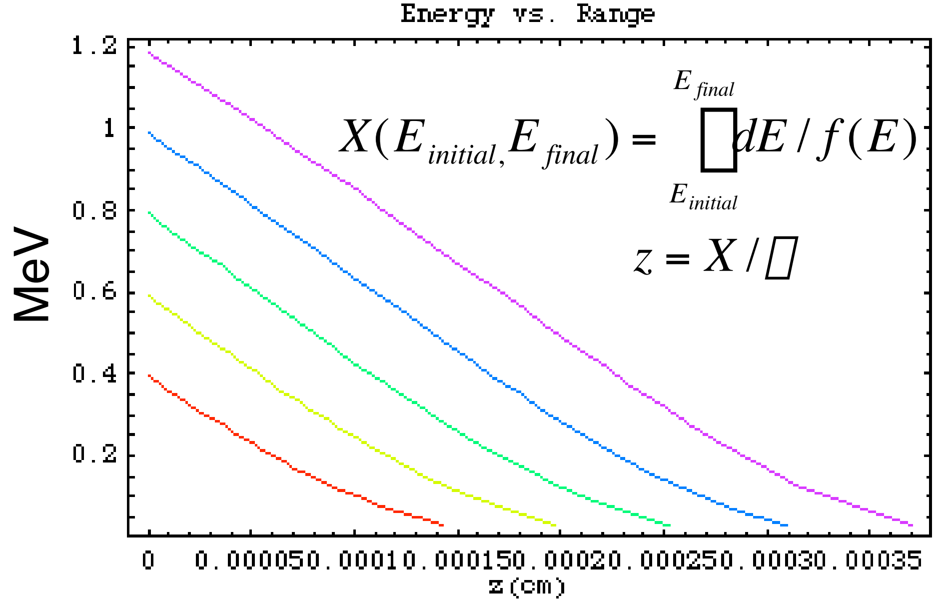
Length of lens
>~ 1 "betatron" or particle oscillation length, so particles are "funneled" to a focus

Velocity spreads $\Delta v/v$ ~ 1 are transmitted;
Ultimate spot size determined by balance between focusing force and beam emittance

We have looked at the effect of a velocity spread on temperature uniformity on target

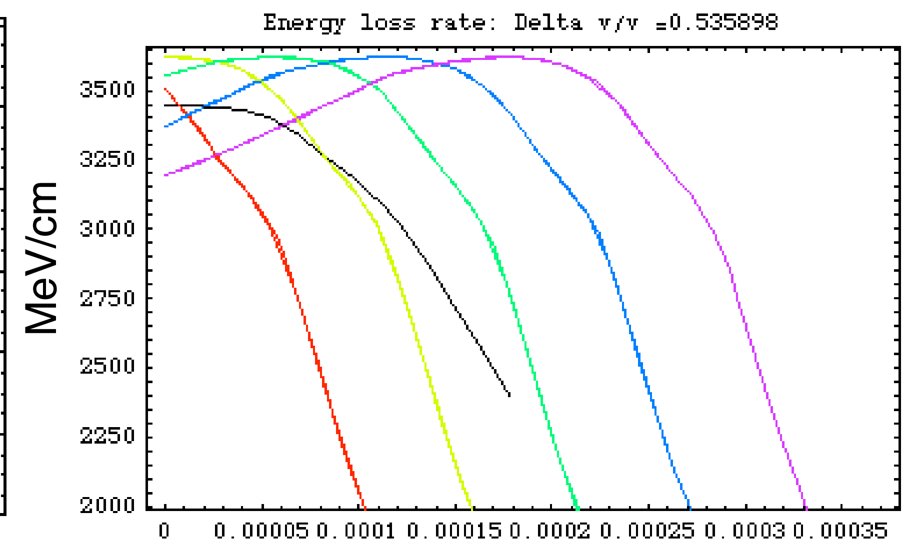




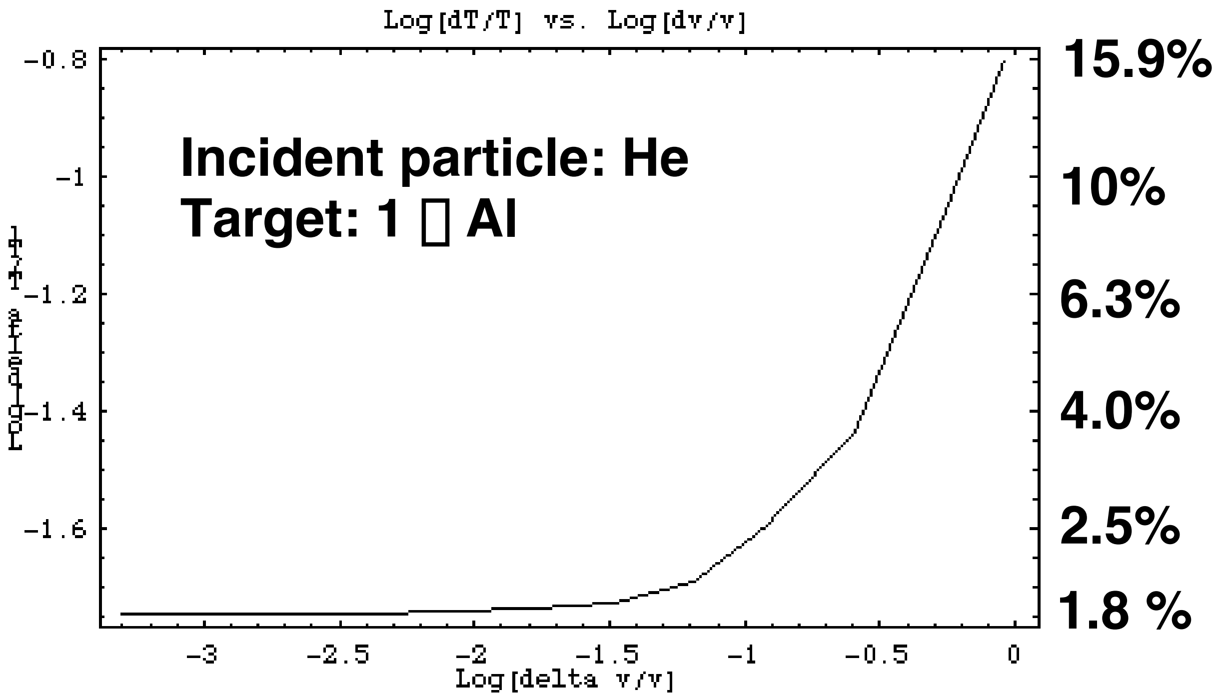


$$X(E_{initial}, E_{final}) = \int_{E_{initial}}^{E_{final}} dE / f(E)$$

$$z = X / \rho$$



Log ΔT/T vs. Log Δv/v



For a uniform distribution of velocities, velocity spread does not reduce Temperature spread. But as long as velocity spread <~ 10%, temperature spread not significantly increased either.
General result: if ΔE_{spread} <~ $\Delta E_{single\ particle}$ then spread does no harm.

Introduction of plasma into beam path, reduces self-field from space charge, but adds other possible interactions

-Filamentation

-Two-stream instability

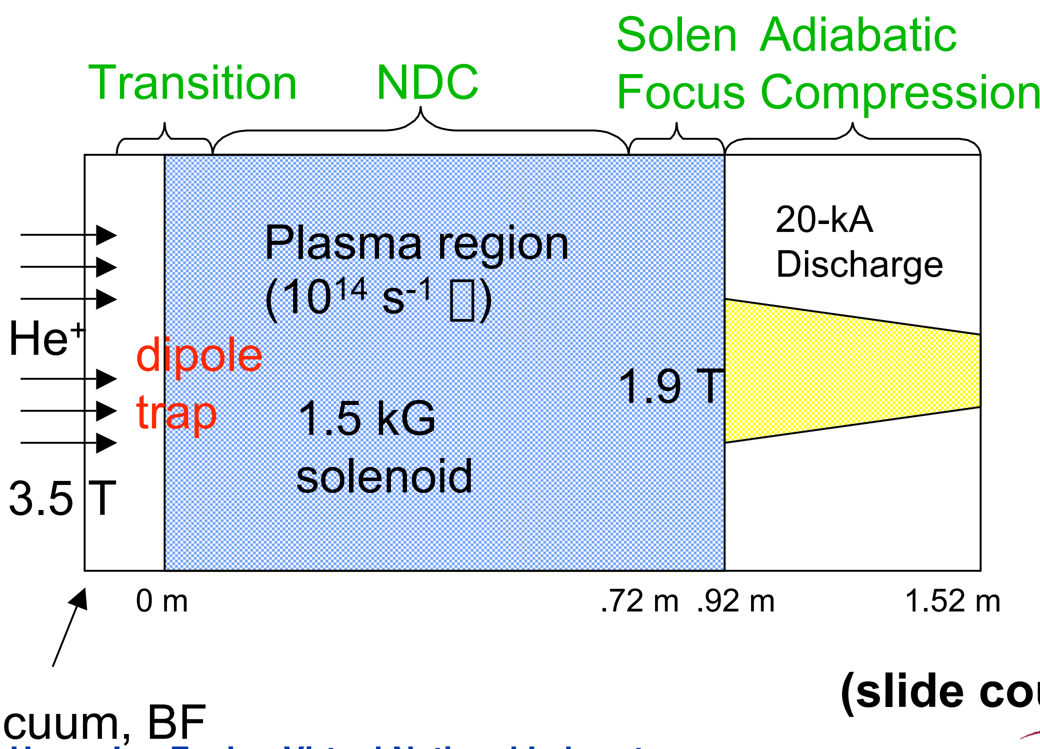
-Electrons drawn into non-neutral beam at transition between accelerator (non-neutral) and drift region (neutral)

-Stripping

These issues are being studied computationally (using LSP code) and will be addressed experimentally in "NDCX" experiments

Phase 2: 10 A, 100-ns He beam at end of accelerator

Compressed from 1-A 1-s beam in accel-decel injector
=1.2-mm-mrad, r=2cm, .75 J
60-cm long adiabatic discharge channel (20 kA); 10 mm to 1 mm radius
67% energy tilt from 500-1000 keV in 100 ns
Need to compress 100x and focus to 1-mm spot to achieve “HEDP”



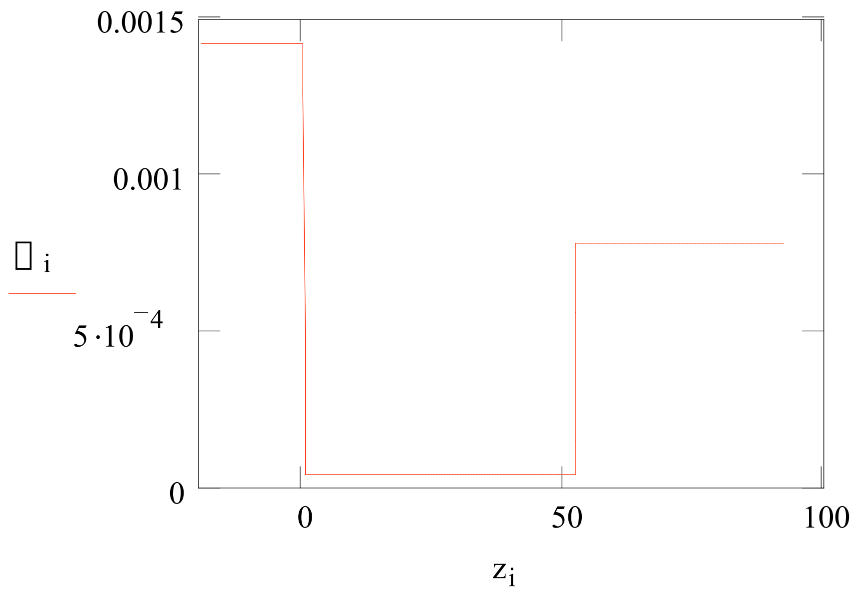
(slide courtesy D. Welch)

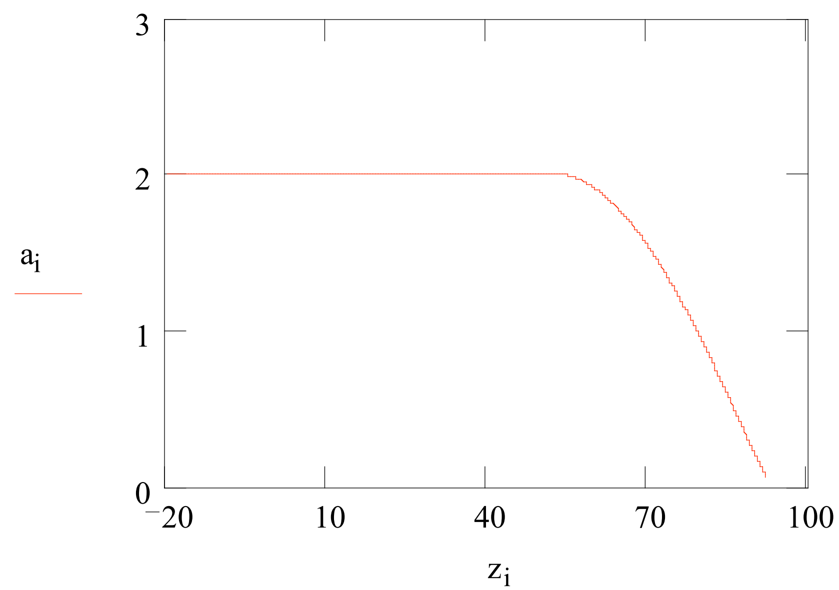
Envelope solution for Brillouin Flow and Neutralized Drift Compression

(slide courtesy D. Welch)

Solution for 750 keV He^+

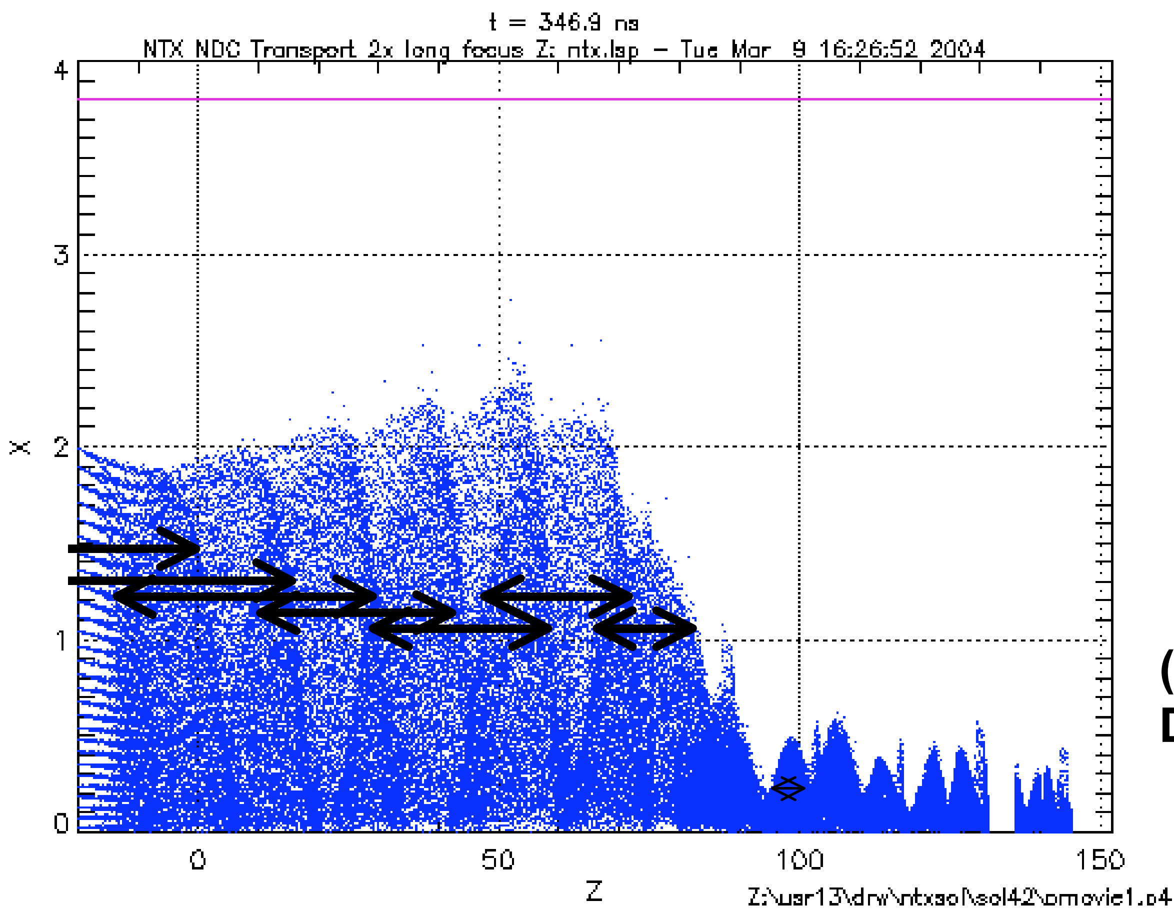
Long 1.9-T,40 cm focusing coil at z = 52-92 cm





Snapshots of Beam Transport

Beam relaxes longitudinally due to incomplete neutralization
Longitudinal "overfocus" to z = 139 gave shortest pulse at z =152



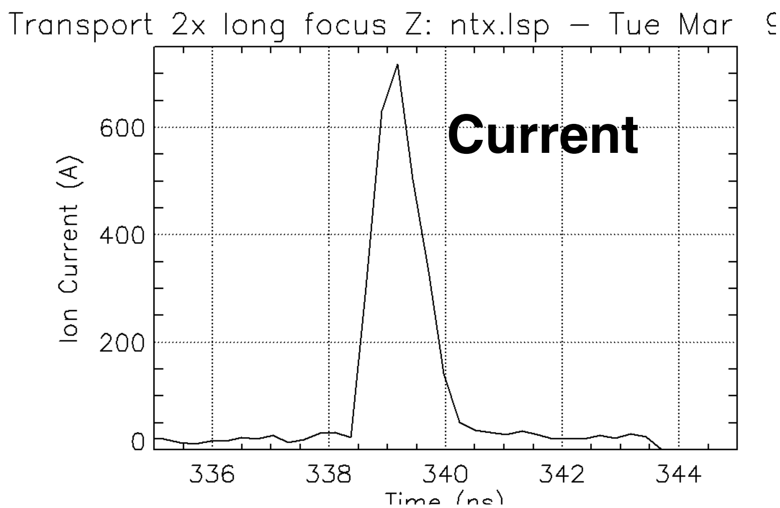
(slide courtesy D. Welch)

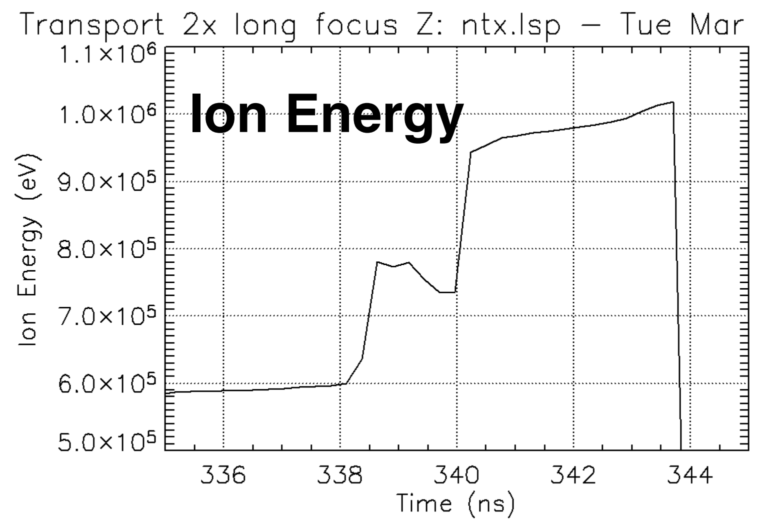
Possible to compensate for less than ideal neutralization

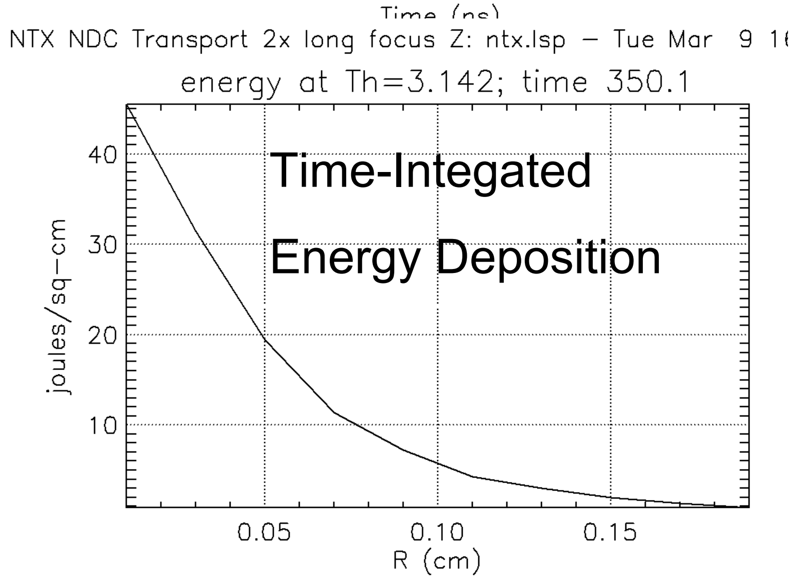
Beam compresses to WDM conditions

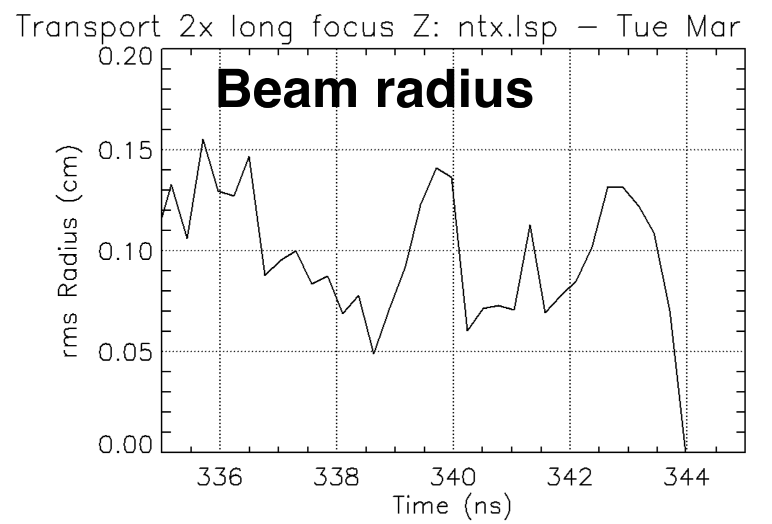
< 1 ns, < 1 mm pulse on target z = 152 cm
Compressed to .75 kA, 75x

(slide courtesy D. Welch)









Conclusion

We are continuing to evaluate the best regime (i.e. target temperature, density, material and configuration) for accelerator-driven HEDP experiments in consultation with "user groups"

Neutralized drift compression and neutralized focusing system appear to be good match for requirements. The physics of beams (particularly propagating through neutralizing plasmas) offers a rich, largely unexplored, area for scientific discovery and potential benefit to other accelerator applications

"Brainstorming" working group (S. Yu, R. Briggs, A. Friedman, E. Lee, G. Logan, J. Marx, A. Sessler, J. Wurtele, J. Barnard) examining wide range of accelerator architectures from rf to induction, from linacs to rings, is scoping out the best accelerator approach for HEDP studies